Modeling Turbulent Burning in Type Ia Supernova Simulations

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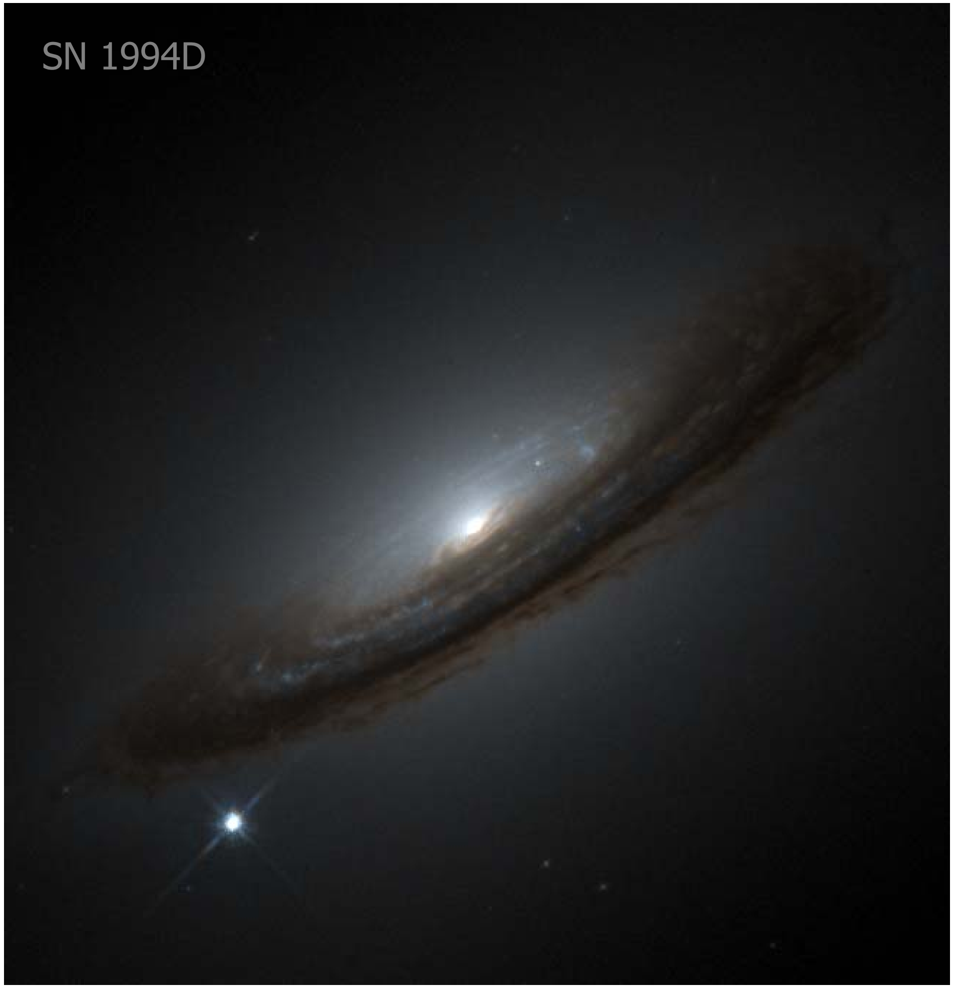
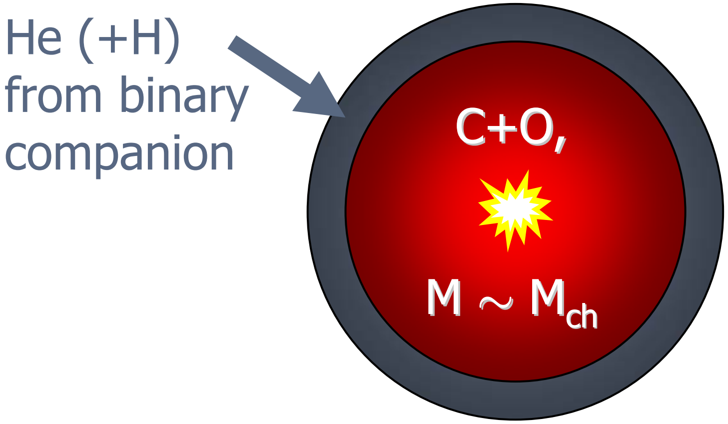
Astrophysical scenario



favored astrophysical model:
thermonuclear explosion of a white dwarf star



Explosion model

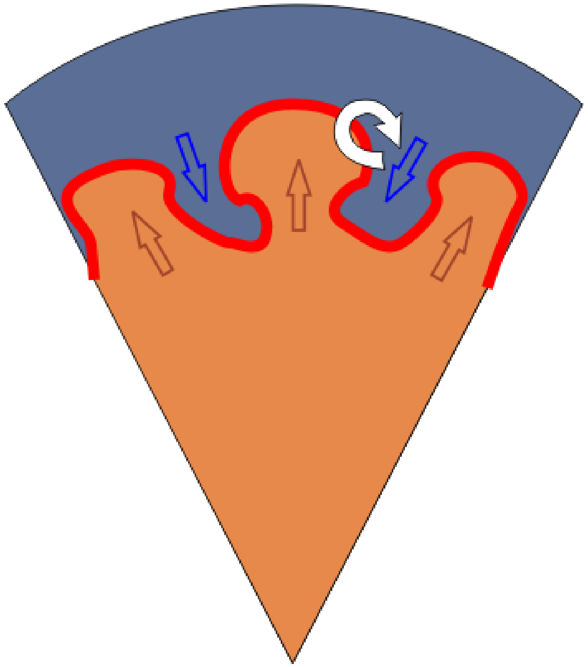
describe flame propagation through WD

- hydrodynamics: 2 modes:

deflagration	detonation
subsonic	(super)sonic
flame mediated by thermal conduction of e^-	flame driven by shock waves

- pure detonation would produce wrong composition of explosion products (Arnett, 1969)
- flame starts out as deflagration (Nomoto et al.)
- problem: laminar deflagration flame too slow
- main issue: acceleration of flame propagation

- interaction of flame with turbulence $\rightarrow$ turbulent combustion
- generic instabilities:



estimate Re around RT-bubble:
$L \sim 10^7$ cm, $v_{shear} \sim 10^7$ cm s^{-1}
$\rho \sim 10^9$ g cm^{-3}, $\eta \sim 10^9$ g cm^{-1} s^{-1}

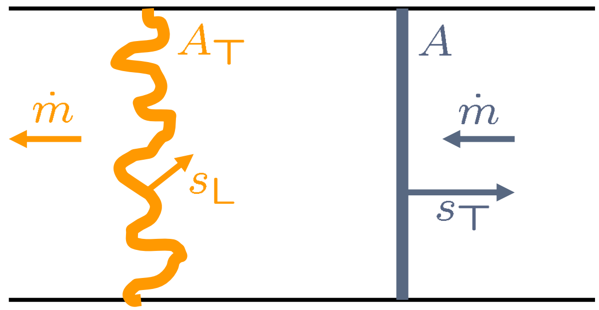
$\rightarrow$ Re $\sim 10^{14}$

formation of turbulent energy cascade

- wrinkling of the flame front $\rightarrow$ flame surface $\uparrow$ $\rightarrow$ net burning rate $\uparrow$ $\rightarrow$ flame propagation strongly accelerated
- later transition to (supersonic) detonation?

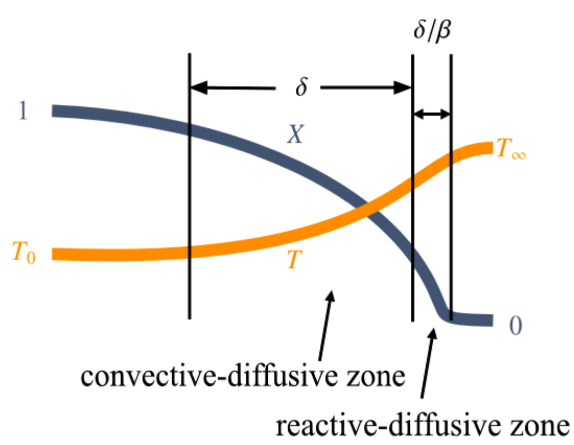
Lessions from engineering

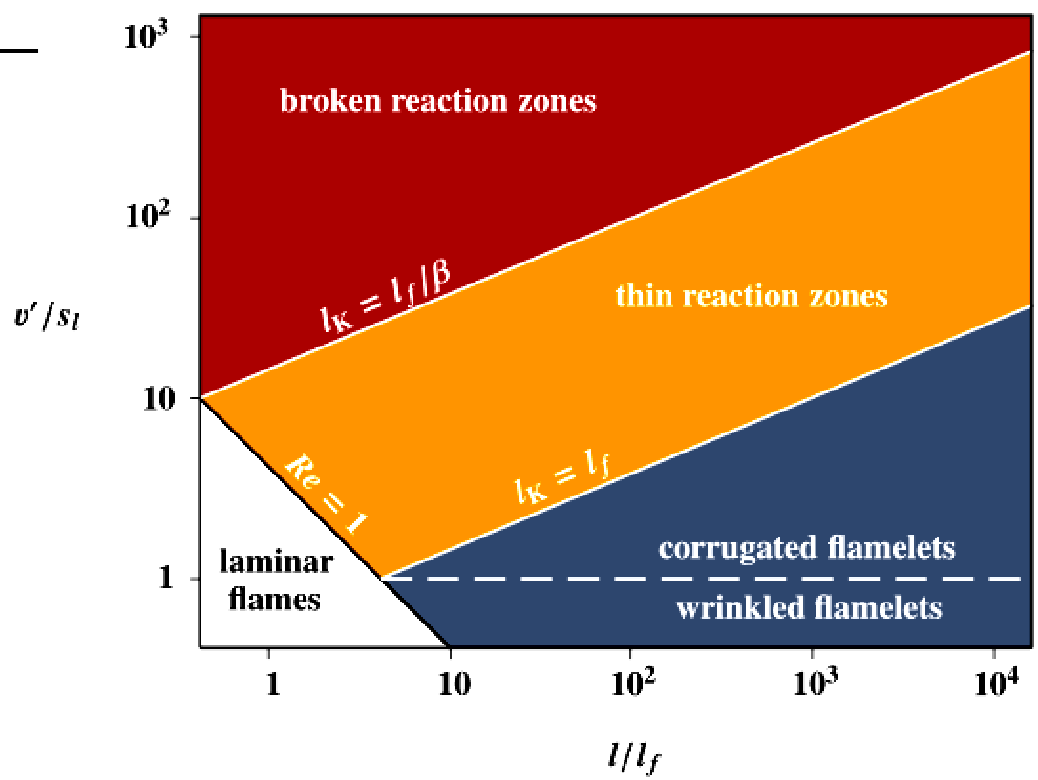
- turbulent burning velocity of the flame → from mass flux conservation:



$$\frac{s_T}{s_L} = \frac{A_T}{A}$$

- Regimes of turbulent combustion (e.g. Peters, 2000)





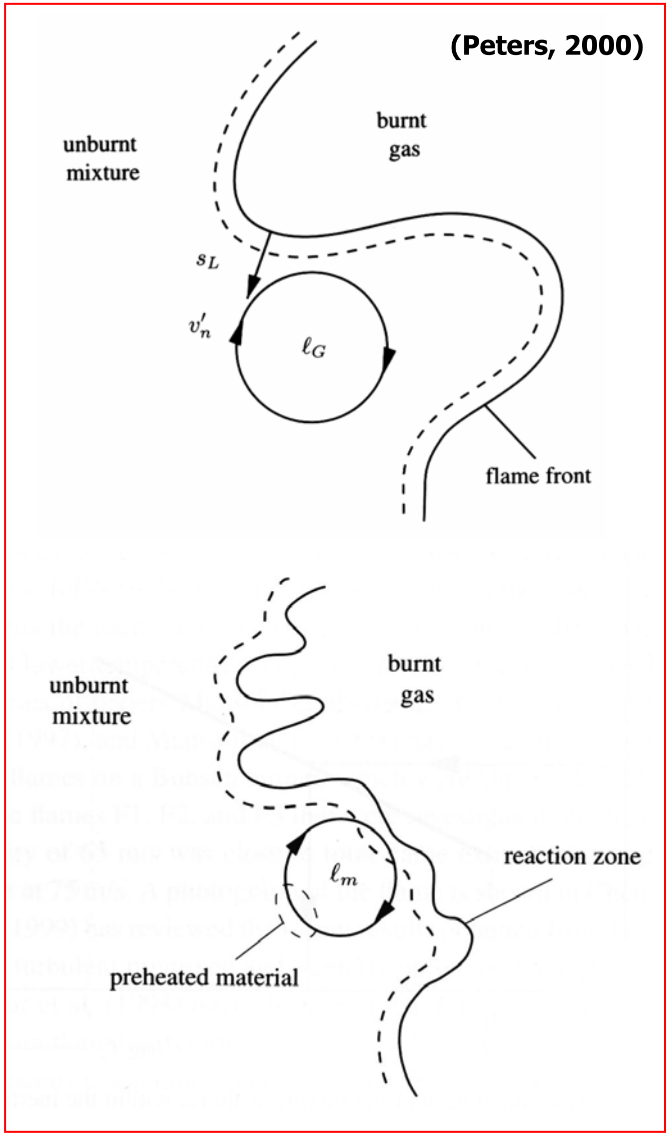
Lessions from engineering

- The flamelet concept
  - flame corrugated on large scales (interaction purely kinematic)
  - internal sturcutre unaffected by turbulence
  - Damköhker (1940):

$$\frac{A_\mathrm{T}}{A} \sim \frac{v'}{s_l} \quad \longrightarrow \quad s_\mathrm{T} \sim v'$$

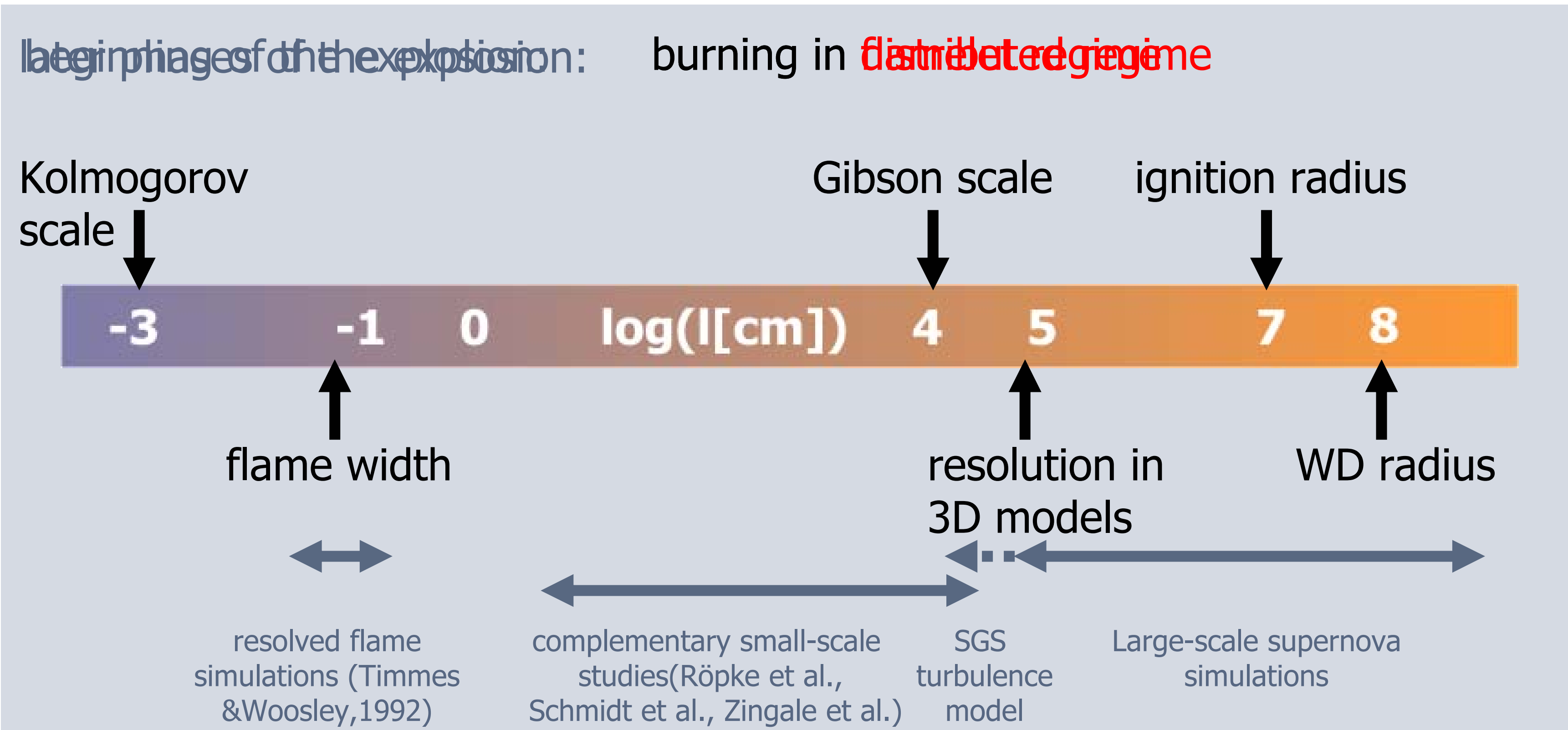
- Transition to distributed burning: thin reaction zones
  - turbulence modifies transport between reaction zone and fuel
  - Damköhler (1940): from $s_\mathrm{L} \sim \sqrt{D/t_\mathrm{C}}$

$$\frac{s_\mathrm{T}}{s_\mathrm{L}} \sim \sqrt{\frac{D_\mathrm{T}}{D}} \quad \longrightarrow \quad s_\mathrm{T} \sim \sqrt{\frac{s_\mathrm{L} v' l}{l_\mathrm{F}}}$$



Simulating the relevant scales

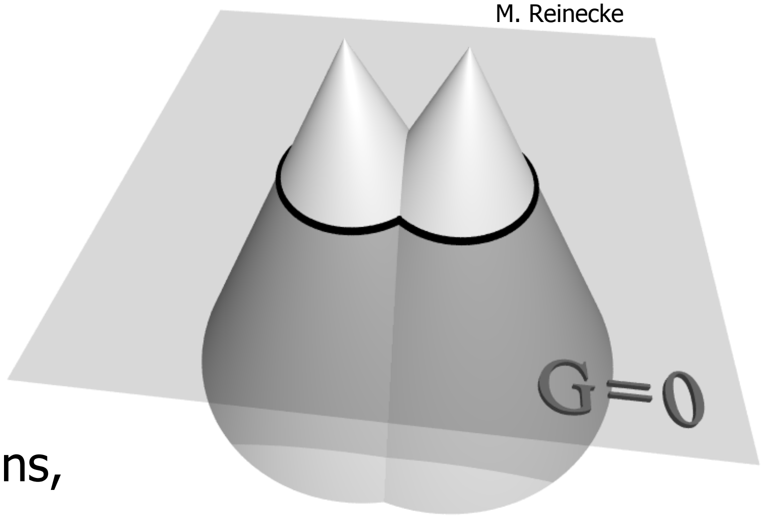
- Gibson scale $s_{lam} = v' \rightarrow$ below turbulence does not affect flame propagation



Numerical techniques

explosion model (Reinecke et al., 1999, 2002) → Large Eddy Simulation approach

- hydrodynamics: finite volume approach → PROMETHEUS (Fryxell et al., 1989) implementation of PPM (Colella & Woodward, 1984)
- turbulence on unresolves scales implemented via sub-grid scale model
- flame model: WD ∼ 10^8 cm structure of flame ∼ 1mm → not resolvable → modeled as discontinuity between fuel and ashes
- level set method



- "flamelet regime" of combustion: turbulent flame propagation velocity determined from sub-grid scale model
- simplified description of nuclear reactions, nuclear postprocessing step (Travaglio et al., 2004)

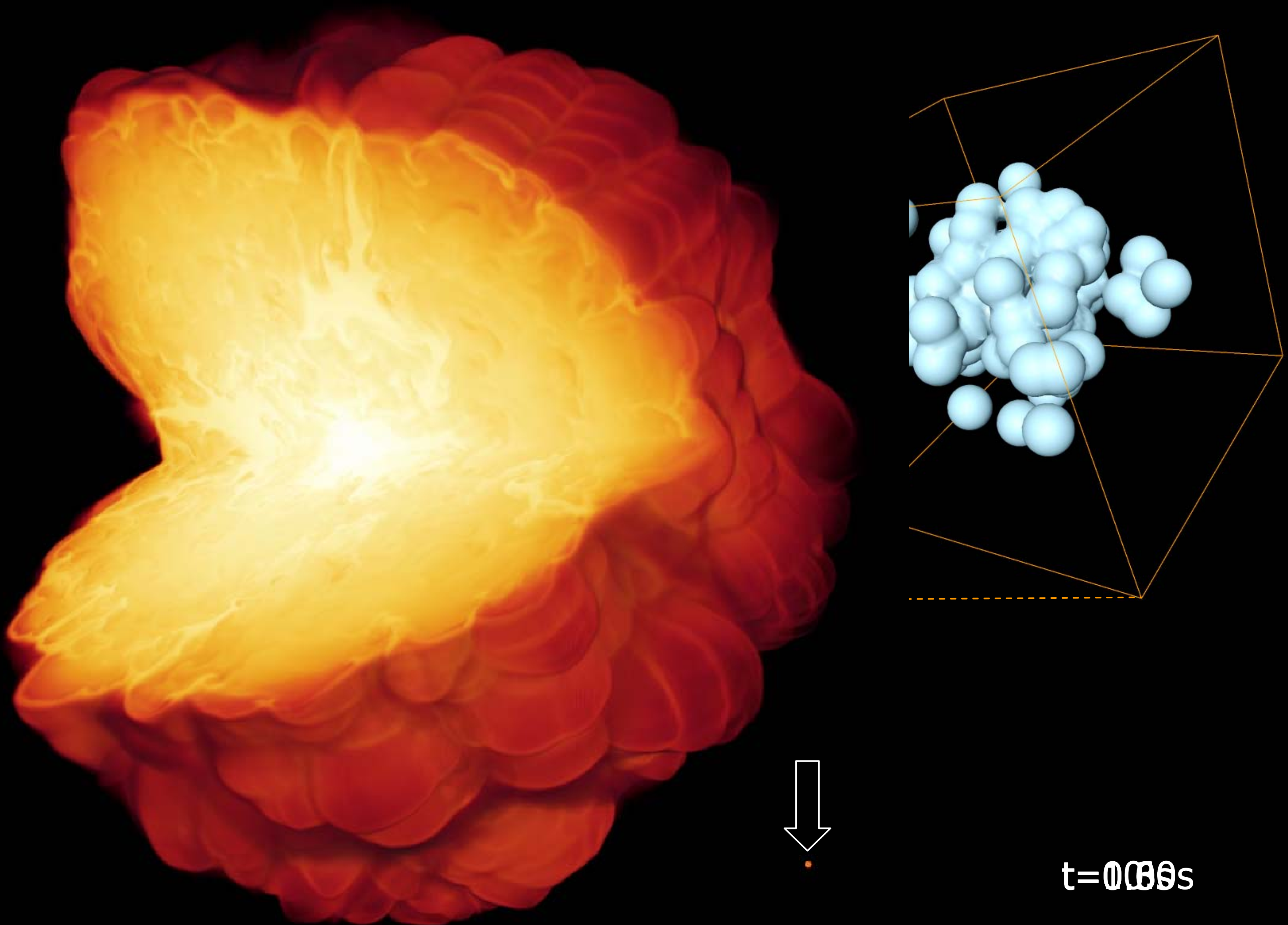
Numerical techniques

- simplified description of nuclear burning (Reinecke, 2002):
  - include 5 species: ^{12}C, ^{16}O, "Mg" $\rightarrow$ intermediate mass elements, "Ni" $\rightarrow$ iron group elements, α-particles
  - at high ρ_{fuel} burn to NSE consisting of "Ni" and α
  - for $\rho_{fuel} < 5.25 \times 10^7$ g cm^{-3} burn to "Mg"
  - for $\rho_{fuel} < 1 \times 10^7$ g cm^{-3} burning is no longer followed

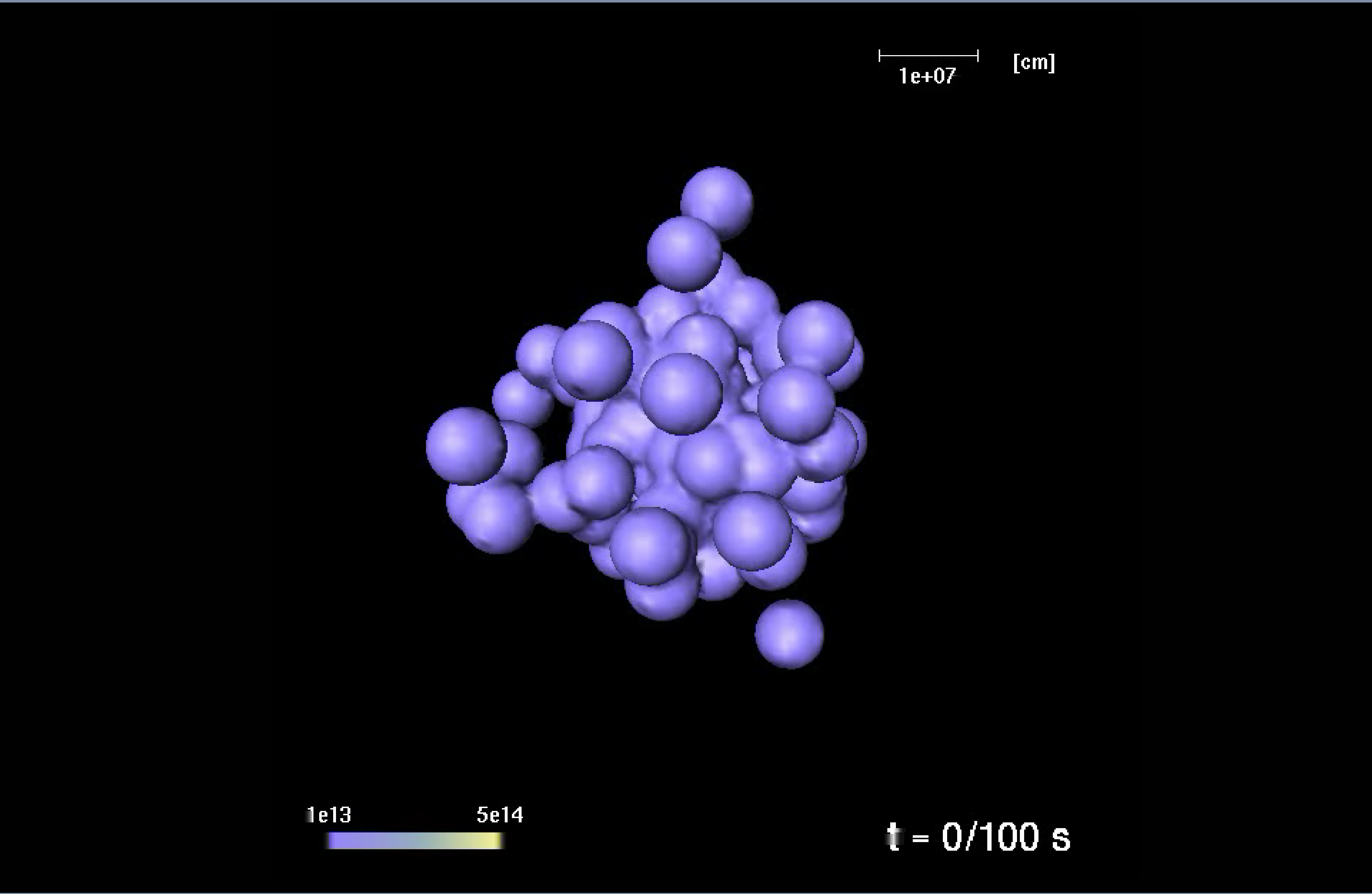
nucleosynthesis postprocessing (C.Travaglio, 2004, M. Gieseler)

- record evolution of density, energy, temperature by tracer particles equally distributed in mass shells (Lagrangian component in Eulerian explosion code)
- use tracer information to perform nuclear postprocessing with nuclear reaction network (384 isotopes) provided by F.K. Thielemann

Large-scale simulations



Flame evolution

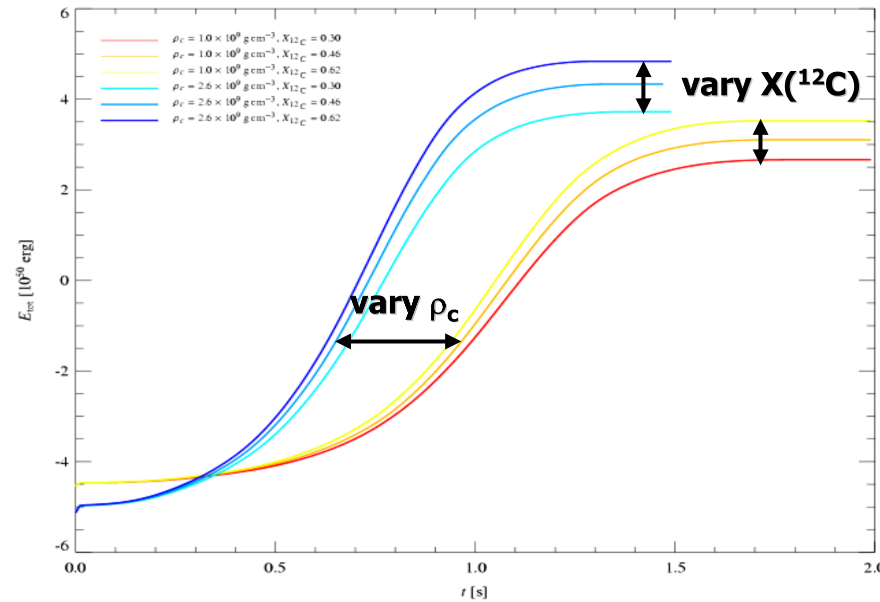


Application of models

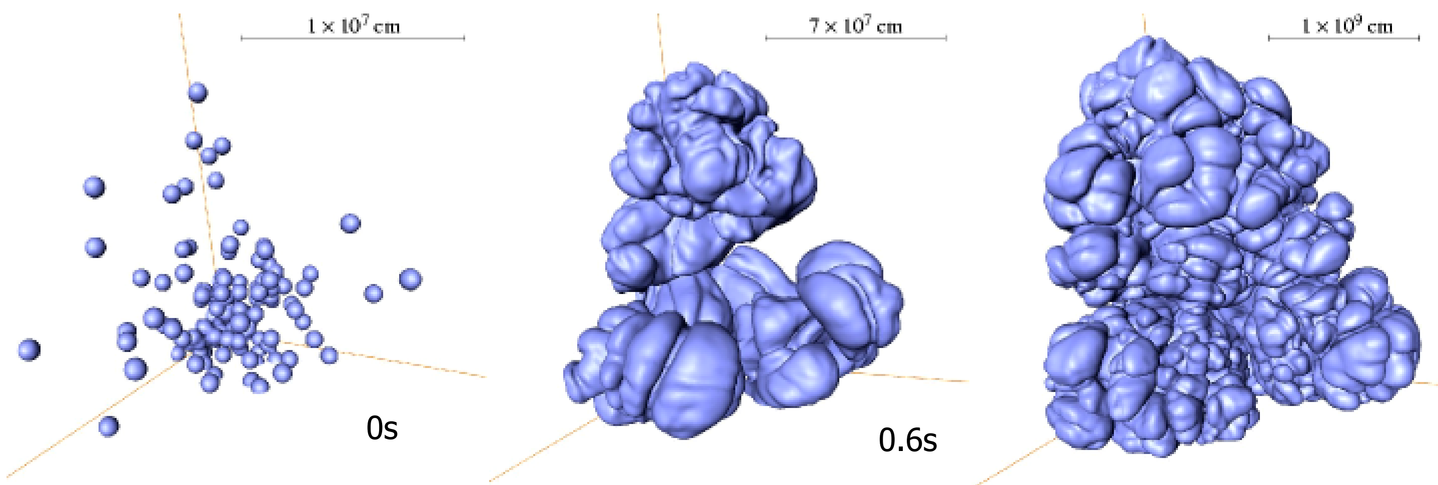
deflagration models recently applied to

- study initial parameters :
  C/O ratio of the WD star,
  central density at ignition,
  metallicity → SN Ia diversity?

  (Röpke et al. 2004, 2005, Travaglio et al., 2005)

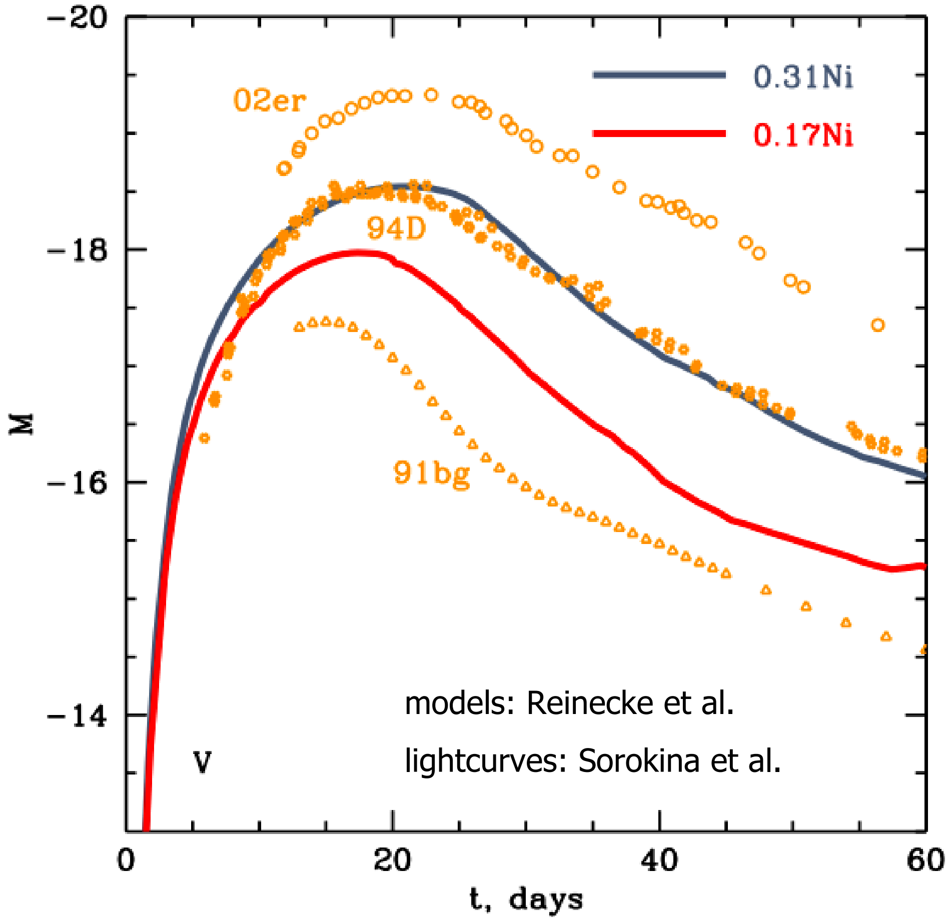


- study multi-spot ignition scenarios (Röpke et al., in prep.)



Status of modeling

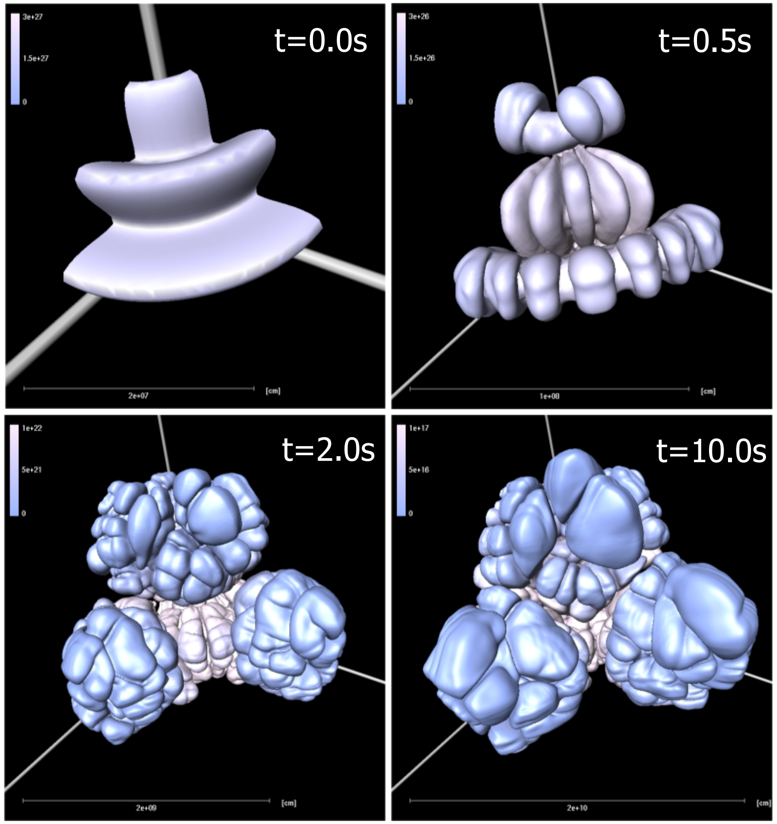
- synthetic light curves:

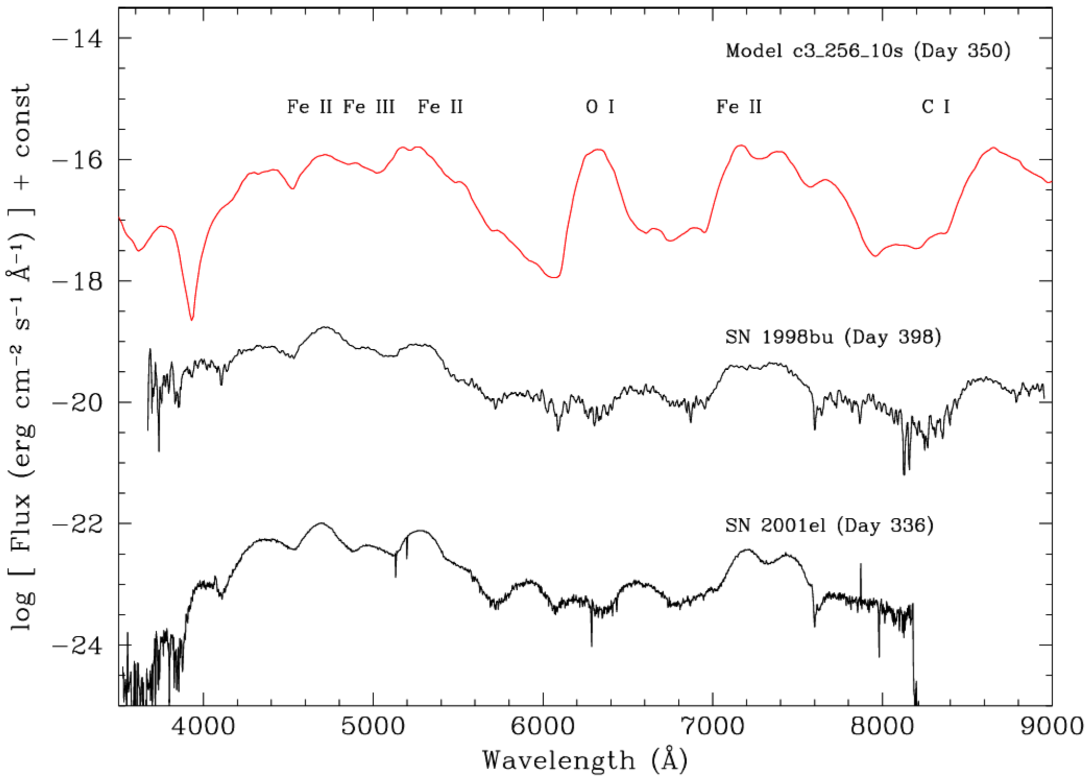


- "best model" (b30, M. Reinecke, 2003): 0.4 $M_\odot$ of ^{56}Ni, 0.7 foe

Problem: nebular spectra

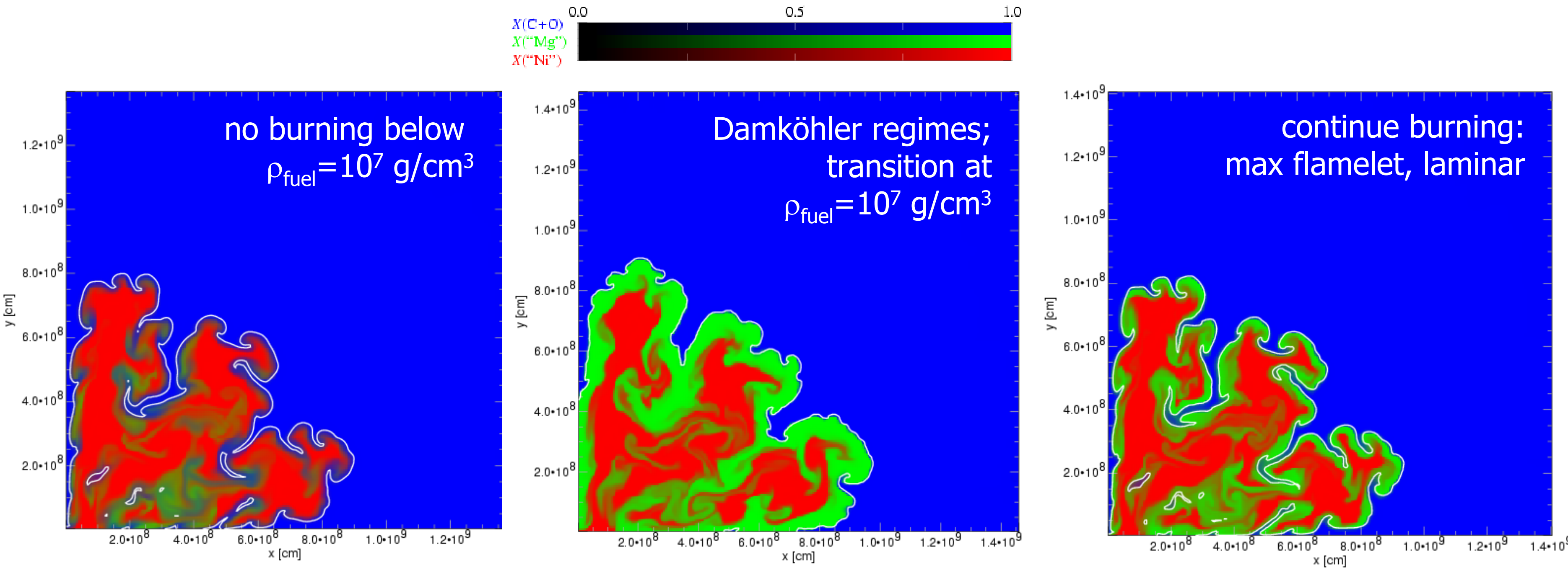
- 3d example → spectrum at day ∼350 (Kozma et al., 2005)





Burning in late phases

- thin reaction zones regime?
- as long as flame thickness $\ll$ integral scale of turbulence: flame on large scales still dominated by turbulence leading to corrugated flamelet regime with modified microphysics $\rightarrow$ still following flamelet scaling



- very late stages $\rightarrow$ ractions slow, flame thickness large $\rightarrow$ volume burning??? $\rightarrow$ depends on turbulence freeze-out due to expansion

Summary and outlook

- deflagrations in type Ia supernova explosions: problem of turbulent combustion
- LES approach suitable for simulations
- reasonable agreement with observations in global quantities (energy, ^{56}Ni production), though on weak side

- cure low velocity unburnt material problem:
  - increase resolution
  - improve sub-grid scale model ($\rightarrow$ W. Schmidt)
  - burning in late phases
  - test initial flame configurations $\rightarrow$ multi-spot ignition
  - delayed detonation?
  - ...